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A Finite Element Modeling (FEM) Approach in Evaluating Fire-Induced Damage in Reinforced Concrete Slabs

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Abstract The study proposes a finite element modeling (FEM) method for analyzing fire-induced damage in reinforced concrete (RC) slabs using ANSYS Workbench. RC slabs experience severe damage in terms of thermal and mechanical degradation under fire exposure, including microcracking, loss of stiffness, and compressive strength weakening. To fill the gaps in the literature on post-fire one-way reinforced concrete slabs, a three-dimensional FEM model was developed using ANSYS software, incorporating Eurocode 2 properties of temperature-dependent concrete strength and steel strength. A Coupled Field analysis was performed using ISO 834 standard fire exposures from 200 ℃ up to 1200 ℃ and exposure durations of 30 minutes to 180 minutes. Validation against published experimental data indicated that there was a close correlation between simulated and experimental results, with the highest deflection difference of 1.484 mm. It was also found that temperature gradients resulted in significant mid-span deflections, tensile cracking, and progressive stiffness deterioration. Regression analysis showed that temperature and exposure time influence the loss of concrete strength, and exposure time is more effective.

Keywords Reinforced Concrete Slab, Fire-Induced Damage, Finite Element Modeling, ANSYS, Crack Pattern, Compressive Strength

1. Introduction

The most employed material in modern structures is reinforced concrete because of its notable strength, durability, and far superior fire-resistance compared to steel and timber frames [1]. However, when exposed to fire, RC elements experience complex thermal, chemical, and mechanical changes, including evaporation of moisture, microcracking, spalling, as well as concrete and steel destruction that has an outcome on reducing their ability to carry weight [2]. Evaluating the compressive strength of RC slabs after fire exposure is essential for post-fire structural evaluation, retrofit design, and ensuring the safety of buildings affected by fire [3]. Due to the complexity of these coupled thermal, mechanical, and material degradation processes, experimental investigation is insufficient to capture RC slab reactions in fire. Therefore, numerical approaches have been increasingly used to simulate these effects and predict post-fire structural performance. Finite element modeling using ANSYS has become very important for simulating the combined structure-thermal reactions of RC components under heat conditions and has provided detailed information regarding the temperature distribution, the stress fields, and failure mechanisms [4]. Despite these advances, most FEM studies have concentrated on beams and columns, with limited studies on one-way RC slabs and their specific post-fire compressive behavior varying across different fire curves and geometric arrangements. Thereby, there is a clear gap that this research seeks to address [5].

Existing research has concentrated on how reinforced concrete elements react to fire through experimental methods and FEM to identify the structural degradation when exposed to heat. Allam [6] used the method of finite difference to analyze the resistance of fire for concrete slabs and concentrated on parameters such as concrete cover and ratio of live loads [7]. Based on the 2011 research conducted by Bo [8], which made use of FEA to simulate fire-induced spalling on high-strength concrete slabs, it was evident that the occurrence of spalling is very important to structural integrity. Furthermore, studies have assessed the post-fire residual flexural strength of RC beams and proposed improved calculation methods that consider the temperature-induced strength calculation [9].

In FEM studies using ANSYS, it is usual to conduct a heat transfer analysis, measure T(x,t), and use them as loads in the structural calculation [10]. When thermal and mechanical fields are solved together in a coupled thermal simulation, it results in improved predictions of stresses and spalling but requires more effort for computations [11]. Since the basic elements in 2D form are not able to capture through-thickness heating, geometry is progressed by adding further details, preferably up to 10 mm mesh refinement from areas mostly exposed to fire in 3D solid modeling [12].

Boundary conditions are applied using fire standard curves (such as ISO 834), implementing heat in the form of convection and radiation, and the heat transfer resistance ratio helps decide if the model needs to resolve each point or lump the time response together. Although beams and columns are thoroughly checked with experiments, only a limited number of fires have been tested on slabs. Therefore, concrete strength predictions for slabs are often based on beams, leading to a margin of uncertainty [4].

Numerical techniques have been used to evaluate temperature-induced damage in concrete structures in recent studies. Ahorro [13] examined the probability of cracking in mass concrete after being subjected to high temperatures produced by cement hydration by using the finite element analysis with Monte Carlo simulation. The experiment proved that non-homogeneous temperature distribution and inhibited thermal deformation are major factors behind tensile stress formation and early age cracking. The result highlighted the necessity of proper thermal modeling and variability of material properties in forecasting the risk of cracking in concrete.

According to Eurocode 2 [14], as temperatures rise, causing concrete and steel reinforcement to become weaker, which can result in reduced strength of the structure. Table 1 reveals that the concrete strength is 95% of the original value when heated to 200 ℃ and only 20% at 800 ℃. It drops to nearly zero when reaching 1200 ℃. This decrease happens because water that chemically reacts with the cement paste leaves, and microcracking appears inside the concrete mixture.

Table 1. Relationships with Stress-Strain of Concrete at Temperature Rises

Concrete Temperature θ	Aggregates in concrete		
(℃)	$f_{c,\emptyset}$ %	$\varepsilon_{c1,\emptyset}$	$\varepsilon_{cu1,\emptyset}$
20	100	0.0025	0.0200
100	100	0.0040	0.0225
200	95	0.0055	0.0250
300	85	0.0070	0.0275
400	75	0.0100	0.0300
500	60	0.0150	0.0325
600	45	0.0250	0.0350
700	30	0.0250	0.0375
800	15	0.0250	0.0400
900	8	0.0250	0.0425
1000	4	0.0250	0.0450
1100	1	0.0250	0.0475
1200	0		

Table 2 shows steel strength drops to 90% of its temperature level at 400 ℃, 47% at 600 ℃, and just 11% at 800 ℃. These reductions are due to the fact that as the density of dislocations and phase transformation increases, the microstructure of steel becomes weaker. Due to the interaction of transfer of heat, material degradation, and reaction of structure at fire exposure, the experimental study is often limited in capturing the full behavior of reinforced concrete slabs.

Table 2. Relationships with Stress-Strain of Steel Strength at Temperature Rises

Temperature Level of Steel (℃)	$f_{sy,\emptyset}$ %
20	100
100	100
200	100
300	100
400	90
500	70
600	47
700	23
800	11
900	6
1000	4
1100	2

As a result, numerical methods, especially finite element modeling, have become tools for simulating fire-induced damage, enabling assessment of temperature distribution, stress, cracks, and residual strength. Validation of the FEM ensures that it is accurate in predicting RC slabs under fire. It involves comparing the numerical outputs with experimental or analytical data on properties like temperature distribution, displacement, and load-bearing capacity. As an example of research, Ab-Kadir [15] developed a model and modeled the heat effect on the temperature of reinforced concrete slabs using ABAQUS.

The study of Balaji [16] was performed relating to evaluating the fire effect of RC slabs utilizing Finite Element Analysis (FEA) of three-dimensional. Comparison of the experimental results and the prediction model confirmed it was reliable. At the beginning, the model needs the essential parameters, including the size and shape of the slab, the properties of concrete and steel, fire exposure guidelines, and boundary conditions. After setting the inputs, a three-dimensional and time-dependent study is run using SOLID70 thermal elements in ANSYS to find the distribution of temperature for the slab when exposed to fire. Afterward, nodal temperatures are applied to a SOLID65 model for the concrete and to either a LINK8 or LINK33 model for the reinforcement. This model allows for changes in the temperature effects on material properties and behavior under combined thermal and mechanical loading. Time-dependent deflections, distributions of stress and strain, and failure scenarios are key outcomes of the simulations. The overall response from the finite element study is validated by comparing it with experimental results and standards of IS456 (2000) and Eurocode 2 (2004), which shows good results for thermal and structural parameters.

The research of Abdul-Razzak [17], in which he created a new FEA technique to predict the behavior and fire resistance of reinforcement slabs. A shell element with eight nodes and the Mindlin/Reissner theory is used to consider transverse shear deformation in the model. This method combines geometric nonlinearity using the total Lagrangian approach and Von Karman strains, while it accounts for nonlinearity in materials such as crushing and cracking in both concrete and steel as the heat rises. Experimentation demonstrates that the material's properties are impacted by temperature, changing its Young's modulus, concrete strength, steel strength, and degradation of strain under heat.

In the research of Kodur [18], a detailed computer modeling approach was used to analyze fire resistance in the reinforcement of fiber FRPs and conventional reinforcement in slabs and concrete with reinforcement beams. An approach on finite elements was created in FORTRAN for FRP, was put to the test by matching existing FRP applications, and was later used to explore how fire may affect the structure. The findings showed that bio-based FRP reinforcements reduce more rapidly under fire than conventional CFRP and result in structural failure unless they are protected by insulation. Fire insulation provided better fire protection for all members, especially for those with bio-based FRP, which had to have additional insulation to match the fire resistance of CFRP-reinforced members. The insights indicate the need for caution in thermal design when utilizing bio-based FRPs in fire-exposed structural applications.

During the 1970s and 1980s, finite element techniques improved the analysis of structures for concrete reinforcement in fire. Early usage of FEM in this field primarily concentrated on understanding heat transfer in reinforced concrete members. Early models functioned with one-dimensional structures while assuming linear behavior for materials as they aimed to detect basic heat conduction and its effects on material properties [19]. From 1990 to 2000, researchers started using coupled thermal and structural analysis, which showed concrete degradation and reinforcement capacity reduction under fire conditions. Studies during this period established that the importance of connections between heated and unheated areas remained essential since adjacent non-heated segments performed as restraints that improved resistance to fire for the concrete structure [20]. In recent years, research on fire-induced behavior in reinforced concrete (RC) structures has become possible through combining multi-physics modeling techniques with data-driven methodologies. These methodologies consider the three complex interactions: thermal heat transfer, material degradation, and structural response for a better estimate of fire-related structural behavior. The multi-physical modeling simultaneously shows their interactive behaviors inside structures of reinforced concrete at elevated temperatures. Research examined high-performance concrete's reaction to rapid heating by examining combined mechanical and thermal developments at the mesoscale during the initial time of vulnerability to fire. This technique gained information about how temperature gradients and heat rates affect material behavior when subjected to extreme environmental conditions [21]. Data-driven techniques, especially machine learning applications, have improved RC structure assessment under fire-induced conditions. By using extensive fire test dataset information, researchers have trained machine learning models to predict structural spalling phenomena and complete structural system behavior outcomes. These models provide quick assessment results and determine important fire performance factors to boost the implementation of performance-based fire design [22].

This research paper contributes to enhancing the safety and stability of the constructed environments in the fire-prone areas by conducting the ANSYS finite element methods on the slabs under fire conditions. This research aligns with SDG 9 that aims at developing a resilient and innovative infrastructure that boosts economic growth and human welfare. It also enhances knowledge on the behavior of structures during fire, as the knowledge is useful in improving their ability to endure the pressures caused by both climate change and the high rate of urbanization. The research also promotes SDG 11 by enhancing safe, resilient, and environmentally friendly cities and populations. Furthermore, it contributes to SDG 13 (Climate Action) by addressing the growing risk of fire due to higher temperatures and more heatwaves, as well as by promoting the understanding of the fire resilience of built infrastructure.

The primary objective of this study is to develop a finite element model (FEM) capable of simulating fire-induced damage in reinforced concrete (RC) slabs using ANSYS Workbench. Specifically, the study aims to: 1. Design an FEM for reinforced concrete slabs that are exposed to fire, utilizing ANSYS. 2. Examine various fire conditions of damage in reinforced concrete utilizing the fire curve of ISO 834. 3. Assess the pattern of cracks in the reinforced concrete slab in ANSYS Workbench. 4. Validate the FEM result of the reinforced concrete slab from the previous experimental data. 5. Predict the fire-induced compressive strength from Eurocode 2 results, where exposure time and temperature level of the fire are the input variables, and the output variable is the compressive strength.

2. Materials and Methods

This part focuses on the methodology for this study, involving an FEM-based program that can simulate the fire-induced damage to reinforced concrete slabs. After this, the study will validate the simulation results by comparing the experimental data from the literature. This research seeks to provide an effective and reliable approach to assessing the fire behavior of RC slab through simulated modeling of thermal exposure and structural response. This flowchart outlines the step-by-step procedure for finite element modeling using ANSYS and predicts the compression strength of reduction using Eurocode 2 (ISO 834). Figure 1: The first step selects Coupled Field Transient in ANSYS Workbench. In Engineering Data, input temperature-dependent properties for steel and concrete (specific heat, tensile strength, compressive strength, conductivity for thermal, density, and degradation curves). Use SpaceClaim to create the slab geometry, specifying the span, thickness, concrete cover, and reinforcement layout. The second step in ANSYS Mechanical: click the model to export engineering data and geometry. Define the mesh by inserting sizing on edges and then generate the mesh. The third step: insert a Temperature boundary condition. Apply the ISO 834 fire curve to the exposed slab surfaces. The fourth step: define simply supported boundary conditions, force, and command (solid65) in structural. The fifth step: run the transient thermal analysis. Transfer the temperature field to the structural analysis. Solve for strain, stress, crack development, and total deflection. The sixth step: right-click the solution to insert the temperature, strain, and total deflection. After that, in the menu bar, click Solve. The seventh step: validate the finite - element outputs by comparing them against published experimental or numerical studies, such as the temperature profiles and midspan deflections. Eight steps perform linear regression (and ANOVA) to quantify the relationship. The last step examines the regression coefficients to identify which thermal variables most strongly drive compressive strength loss. Discuss observed failure mechanisms such as cracking.

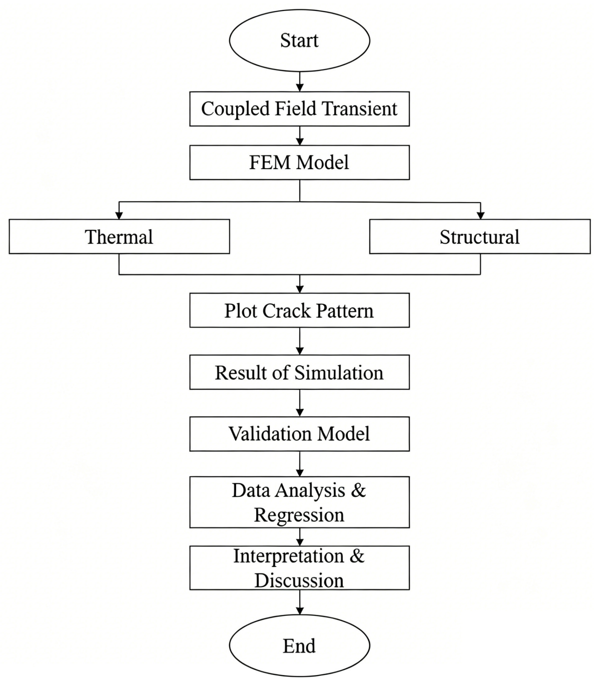

Figure 1. Flowchart of Coupled Thermal and Structural FEM Methods

2.1. Research Design

This research utilized a quantitative method simply because it is simulation-based research with the use of numerical experimentations to measure thermal and structural performance. To begin with, a three-dimensional FEM of a typical section of RC slab with concrete and steel reinforcement will be developed in ANSYS Workbench with correct geometry, meshing, and boundary conditions. The structural analysis is also combined with temperature-dependent material degradation to get total deformation and strain reactions at high temperatures.

2.2. Data Collection Methods

Research data will be gathered from previous experimental tests on slabs of reinforced concrete exposed under heat conditions. The following experimental data are summarized in Table 3, providing essential information on slab geometry, material properties, boundary conditions, and loads.

Table 3. Summary of Experimental Data of RC Slab

Description	Reinforced Concrete Slab
Geometry	3300 mm x 1200 mm x 200 mm
Material Properties	Concrete: Ratio of Poisson 0.2, 42 MPa Compressive Strength, Density 2400kg/m^3, Elastic Young Modulus 39300MPa, Conductivity of Thermal 1.67 w/m C, Thermal Capacitance 1.8 J/C, Thermal Expansion Coefficient 12x10^-6. Steel: Ratio of Poisson 0.3, Tensile Strength 460 MPa, density 2400kg/m^3, Elastic Young Modulus 210000 MPa, Conductivity of Thermal 75 w/m, Thermal Expansion Coefficient 12x10^-6.
Boundary Condition	Simply Supported
Loads	Point Load 27 Kn (at Mid Span)
References	Ali, F., Nadjai, A., Abu-Tair, A., "Experimental and Numerical Study on Performance of Concrete Slabs Subjected to Severe Fire," Fire Safety Science, vol. 9, pp. 1255–1266, 2008, doi: 10.3801/iafss.fss.9-1255.

2.3. Limitations

Limitations throughout this research include cracking, and the following did not include moisture migration, pore pressure, spalling, mesh convergence analysis, the elastic modulus reduction, and the ratio of Poisson after exposure. Simulation assumes that the concrete and steel reinforcement were perfectly bonded and the material properties were homogeneous. The boundary conditions are simplified, disregarding possible temperature gradients caused by irregular fire exposure or variation in the environment.

2.4. Comparison with Other Design Codes

ACI 216 (alternatively TMS 216) is the code requirements standard used to establish the resistance of fire for masonry and concrete, which depends on the standard fire curve ASTM E119 as a method to model fire exposure. The limitation does not explicitly address bond degradation or transient creep, and it mainly focuses on the heating phase rather than the cooling phase. ISO 834 and ASTM E119 are not the same, but they are very similar. ASTM E119 is utilized for testing non-load bearing and load-bearing elements with a strong focus on North American building codes. ISO 834 is used as a basis for European (EN) and international standards focusing on fire resistance in building structures. The fib model code for concrete focuses on modeling the penetration of chloride ions and carbon dioxide that result in reinforcement corrosion. The model is based on physical-chemical processes rather than empirical rules.

3. Results and Discussion

3.1. Meshing

After generating the mesh of the reinforced concrete slab model in ANSYS, the model contains 275 elements and 1506 nodes. Figure 2 illustrates the finite element mesh division number for the concrete reinforced slab with a span of 8, a width of 8, and a thickness of 4. Figure 3 represents the rebar configuration.

3.2. Coupled Field Transient Result

At time exposure zero, 20 ℃ is the starting temperature. The temperature was shown in Figure 4 after it was entered into ISO 834 in temperature. This temperature difference across the specimen indicates that the maximum temperature was approximately 1200 ℃ at the surface where the fire was exposed, and the lowest temperature was approximately 20 ℃ at the side not in contact with the fire, which indicates that the heat flow along the conduction pathway on the exposed face to the inside, is uneven with maximum heat transfer at the surface and minimum at the side. The high thermal gradient close to the exposed face of the fire indicates rapid temperature increase, whereas the unexposed face is severely delayed in terms of increase in temperature due to the insulation effect of the concrete mass. This action is in line with the poor thermal conductivity of concrete and increased capability to heat, which slows heat penetration. The results also confirm that the applied ISO 834 was used appropriately in the numerical model, as observed in the realistic range of temperatures and distribution. This non-equilibrium in the temperature field is valuable in the estimation of thermal strains, redistribution of stress, and ultimate degradation of mechanical properties, which directly influence the deflection of reinforced concrete slabs and the overall performance of a structure.

Figure 5 demonstrates the time dependence of temperatures under the fire exposure situation used. The temperature curve is in accordance with the standard fire behavior specified by ISO 834. The temperature rapidly increases during the first heating stage and then rises more slowly as the time of exposure elapses. It starts at a temperature of around 26 ℃, then continues to get up to around 1200 ℃ after 180 minutes of exposure to fire. The temperature time contours are showing a sharp temperature gradient at the initial exposure stages, with a high heat transfer rate as well as quick thermal penetration through the structural element. The longer the period of exposure, the lower the temperature increase, and this indicates that there is minimal heat transfer as the material is thermally saturated. This is an implication that the most severe thermal effect is experienced in the first stage of exposure, which is very important when analyzing structural response and deflection behavior under fire conditions.

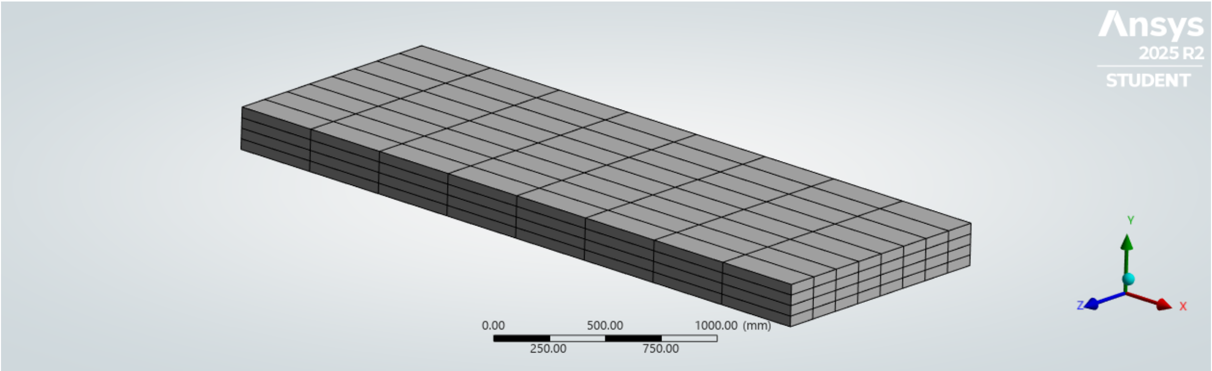

Figure 2. Concrete Element Configuration

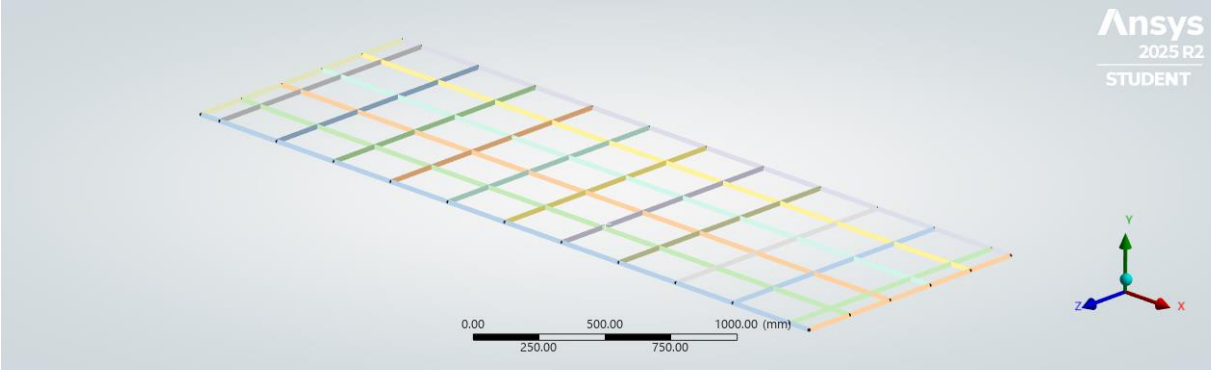

Figure 3. Rebar Configuration

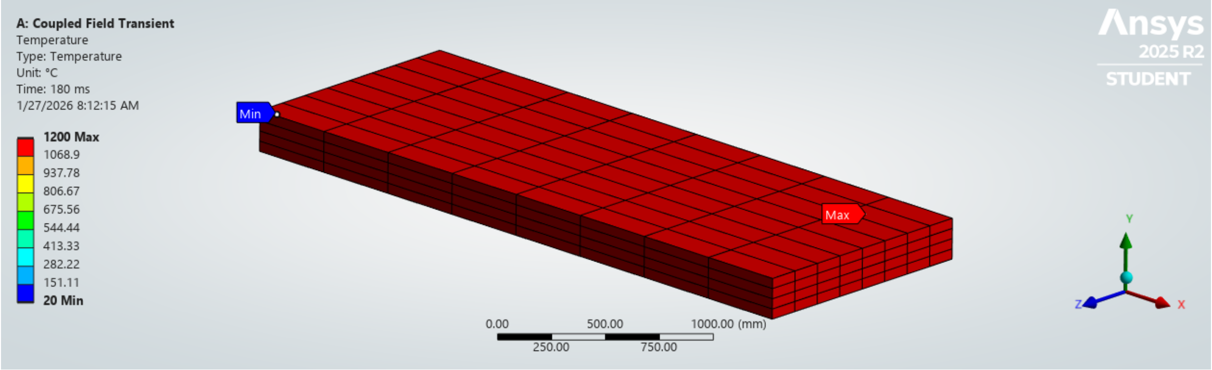

Figure 4. Temperature Result

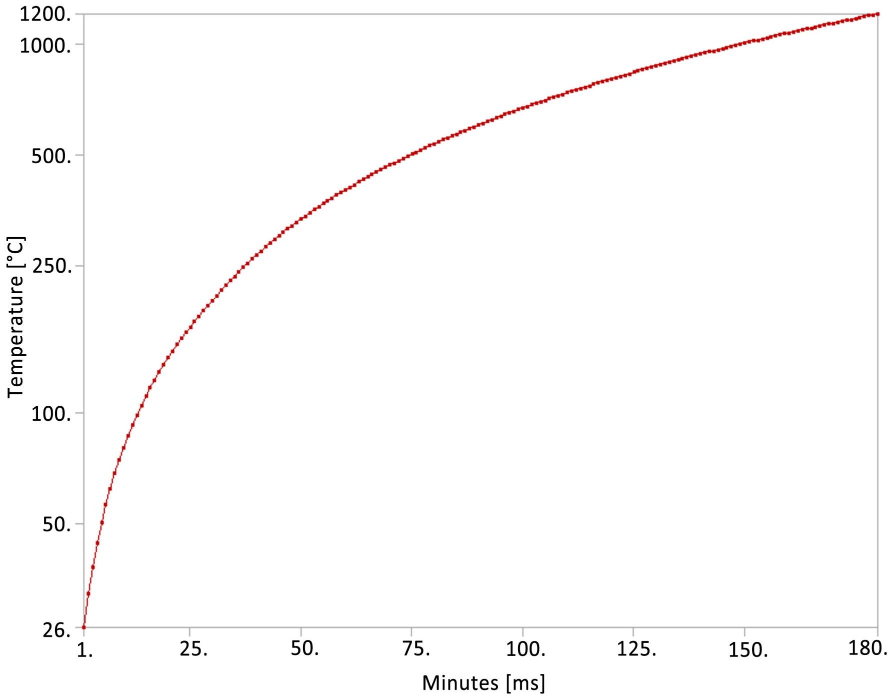

Figure 5. Fire Curve Result at 180 min

After the thermal result was obtained, the analysis was moved to the structural result. ANSYS 2025 R2 was used to analyze the total deformation of the reinforced concrete slab under fire conditions using a Coupled Field Transient simulation. As shown in Figures 6 and 7, the maximum deformation was 28.216 mm at 60 minutes in mid-span, whereas the lowest value in the deformations was at the supports of the slab. The pattern of deformation shows the effect of the non-uniform distribution of temperature and thermal expansion, which caused the slab to deflect downward in the central zone. The findings affirm that higher temperatures have a great impact by lowering the stiffness and concrete slab capacity underload, resulting in greater deformation each time it is exposed to fire.

The coupled-field transient results in Figure 8 indicate that in 180 minutes of fire, the reinforced concrete slab experiences a maximum total deformation of 54.455 mm. The contour shows that the global flexural response is leading, due to thermal expansion and a loss of the heat-dependent material behavior in both reinforcing steel and concrete. As the temperature increases according to the fire curve of ISO 834, both concrete and steel mechanical properties degrade. Moreover, a temperature gradient through the slab thickness would create a thermal rising effect, in which the heated surface would increase more than the unheated one, resulting in greater deformation. The results show the importance of thermo-mechanical coupling to fire-induced deflection behavior and the evaluation of RC slab performance at elevated temperatures.

The result of the strain distribution in the reinforced concrete slab at 180 minutes is shown in Figure 9. The outcome indicates that the strain value ranges between -0.17716 mm/mm (maximum) and -0.80798 mm/mm (minimum). The highest concentration of strain occurs at the mid-span (highlighted in red), which is the area that is undergoing the greatest bending and thermal loading. This localized strain indicates the inclination of tensile cracking in the tension zone of the RC slab caused by both the effects of temperature gradient and deformation of the structure. In a while, the low strain values (in blue) are seen to occur around the slab supports, where the structural restraint restricts the deformation. The change in high and low strain values in a gradual manner indicates the nonlinear character of the deformation of the slab when it is exposed to fire. This reaction indicates that the presence of thermal expansion and degradation of concrete stiffness also lead to the deflection pattern that is observed. The result confirms that the location of the peak strain is also in the critical area where cracks or failure initiation is expected to occur, and this reflects the normal performance of RC slabs in extreme temperatures.

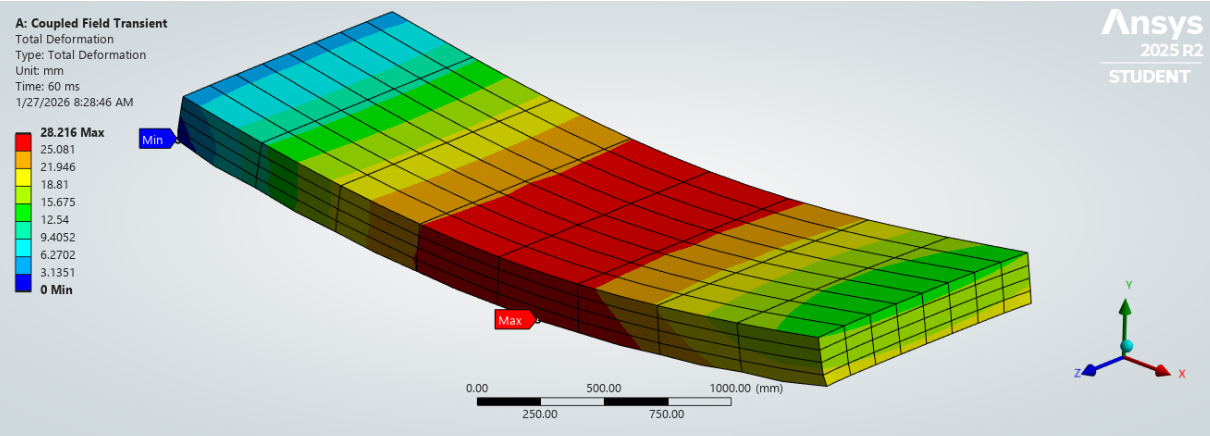

Figure 6. Mid Span Deflection of RC Slab Under ISO 834 Fire Curve at 60 min

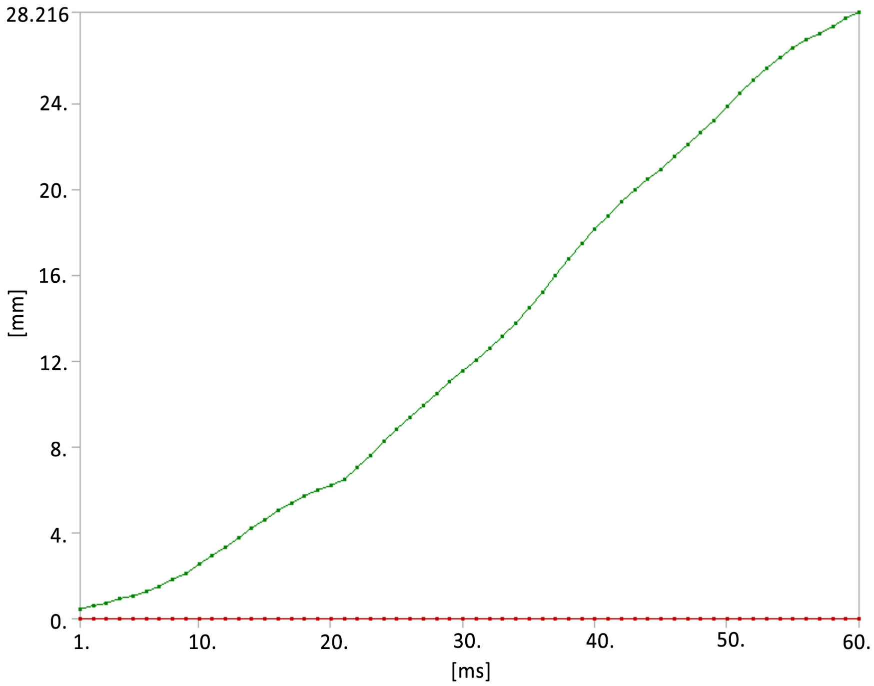

Figure 7. Deflection–Time Response of RC Slab

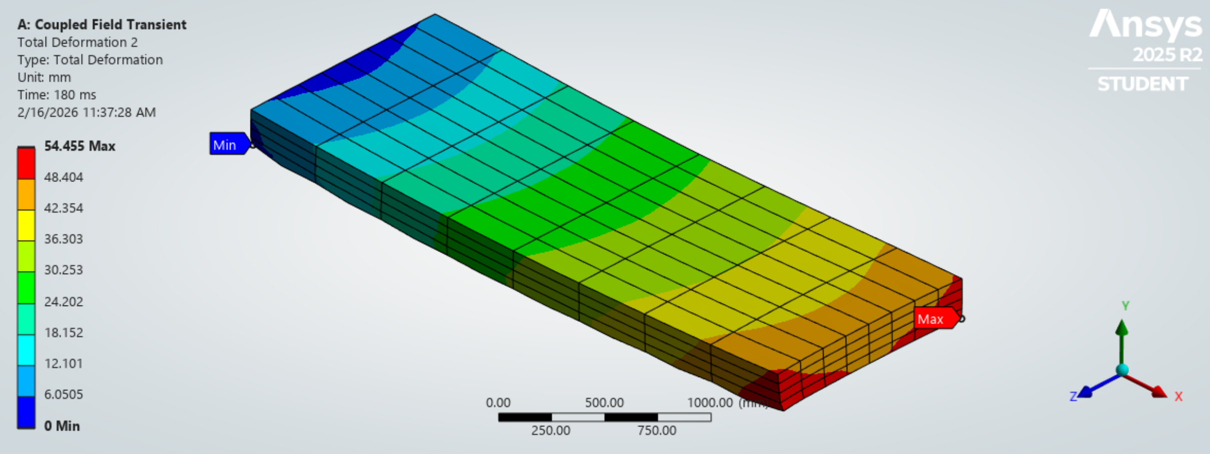

Figure 8. Deflection of RC Slab Under ISO 834 Fire Curve at 180 min

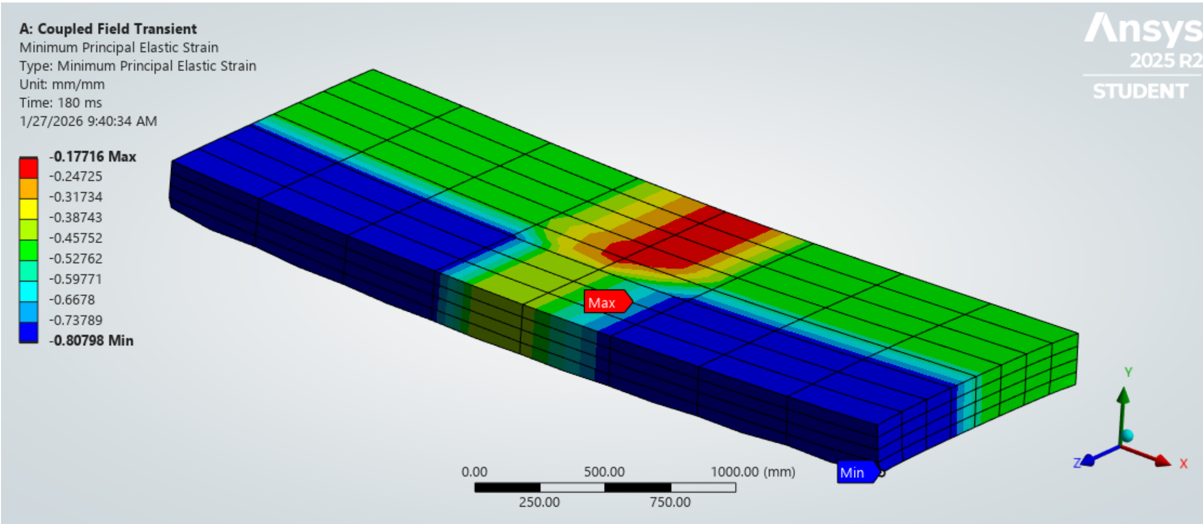

Figure 9. Reinforced Concrete Slab Minimum Principal Elastic Strain

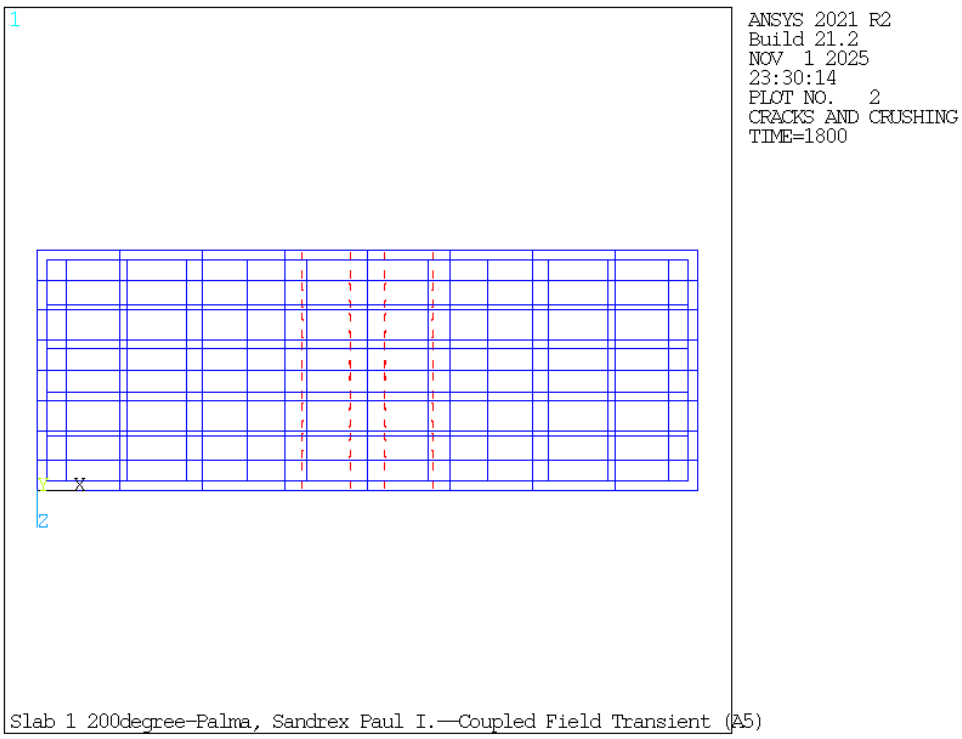

Figure 10. Reinforced Concrete Slab (Bottom View)

3.3. Crack Pattern

The results of the ANSYS simulation at the end of the 1800-second (30 min) coupled-field transient analysis showed the development of cracks in the reinforced concrete slab of the mid area exposed to a heat of 200 ℃. In Figure 10, a series of red parallel cracks were visible in the central area of the slab, and they were transverse to the length of the slab. Figure 11 also confirms the existence of red markings of cracks on the surface at the bottom. Cracking was mostly concentrated in the middle section; on the other hand, the outer edges and support regions were relatively intact, indicating that the greatest stress and concentration of temperature were at the mid-span section. Exposure to fire causes the heated exposed area to expand and the unexposed cooler area to restrain the deformation of the heated structure under thermal gradients, causing bending stress. No considerable compressive crushing was observed in the analysis, and this implies that tensile cracking instead of compressive failure is the dominant mode of damage at this stage. Therefore, the slab still has some structural capacity, but the appearance of cracks indicates a decrease in stiffness and a growth in mid-span deflection.

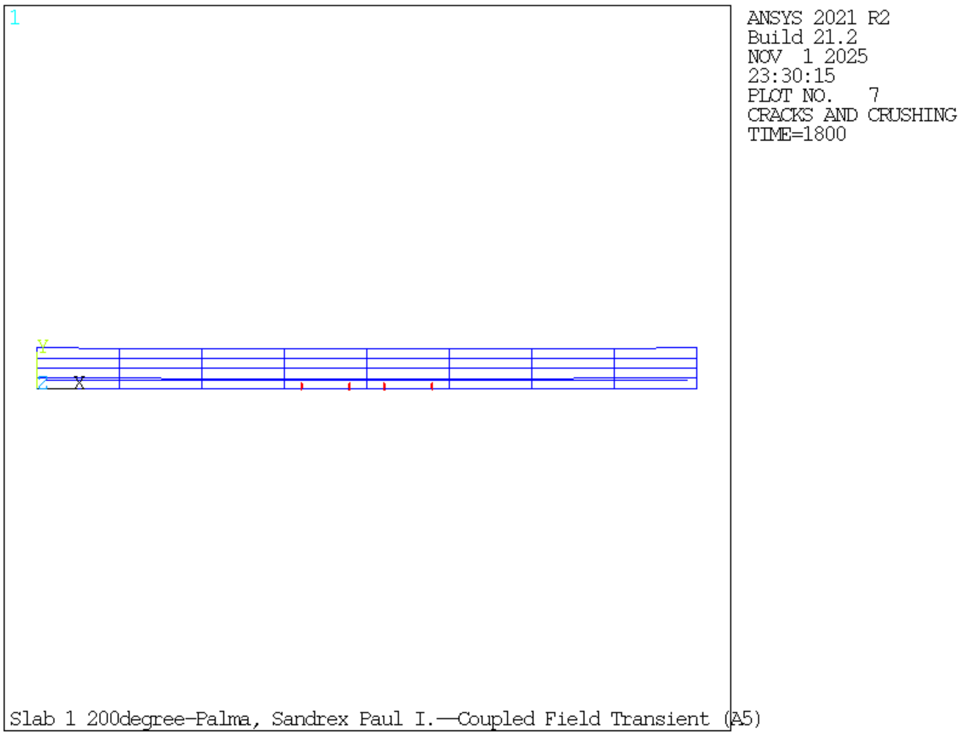

Figure 11. Reinforced Concrete Slab (Side View)

3.4. Validation

The results of the past experimental work of reinforced concrete slabs under BS 476 and the fire curve for Hydrocarbon are provided in Table 4, and the finite element model (FEM) deformation model is provided in Figure 6 of the ANSYS simulation. According to the experimental data, the first deflections of slabs under BS 476 fire were 29.7 mm, whereas under the Hydrocarbon fire, they were 43.9 mm; the greater deformation was because of the higher temperature and faster temperature rise. The simulation of the FEM in ANSYS revealed the highest deflection of 28.216 mm, which was concentrated primarily in the middle of the slab, which is typical of flexural characteristics in the presence of thermal loading. The model is highly accurate because the numerical outcome is very close to the BS 476 experimental outcome, with a difference of 1.484 mm.

Table 4. Results of Experiment Data of RC Slab

Fire Curve	Slab Ref	Max Deflection
		mm
BS 476	S1	29.7
	S2	32.1
	S3	34.2
Hydrocarbon	S4	44.8
	S5	44.7
	S6	43.9

Figure 12 ANSYS result fire curve shows a similar upward trend to Figure 13 experimental furnace results with BS 476 and Hydrocarbon fire conditions. Both exhibit a rapid increase in temperature within the initial few minutes, then a slow increase to around 1200 ℃ at 60 minutes. The ANSYS result still shows a smoother and slightly lower temperature profile than the experimental BS 476 curve, which has slight variations caused by real furnace variations. The simulated curve also falls between the BS 476 and Hydrocarbon tests, which indicates that the conditions of the applied boundaries and material properties in ANSYS are close to the behavior of the fire exposure.

3.5. Regression Model Result

Regression analysis was conducted to predict the relationship between compressive strength reduction, temperature, and time exposure, based on Eurocode 2 data. Table 5 presents compressive strength results at varying temperature levels and exposure durations.

Table 6 showed that the model resulted in a Multiple R value of 0.9723, which is a stronger relationship between predicted and observed values. The value of R^2 of 0.9454 indicates that the regression model explains the data extremely well. Adjusted R^2 equals 0.9317, which also shows that the model of regression is highly consistent and fits well. Moreover, the 0.0011 significance F value is below 0.05, meaning that the correlations between compressive strength reduction vs temperature and compressive strength reduction vs time exposure are statistically significant.

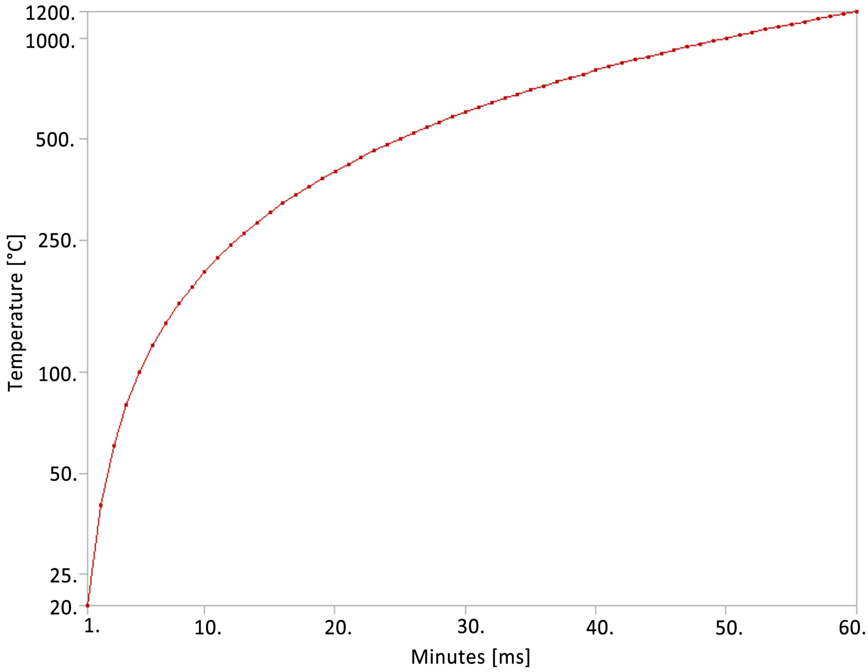

Figure 12. ANSYS Result: Fire Curve at 60 min

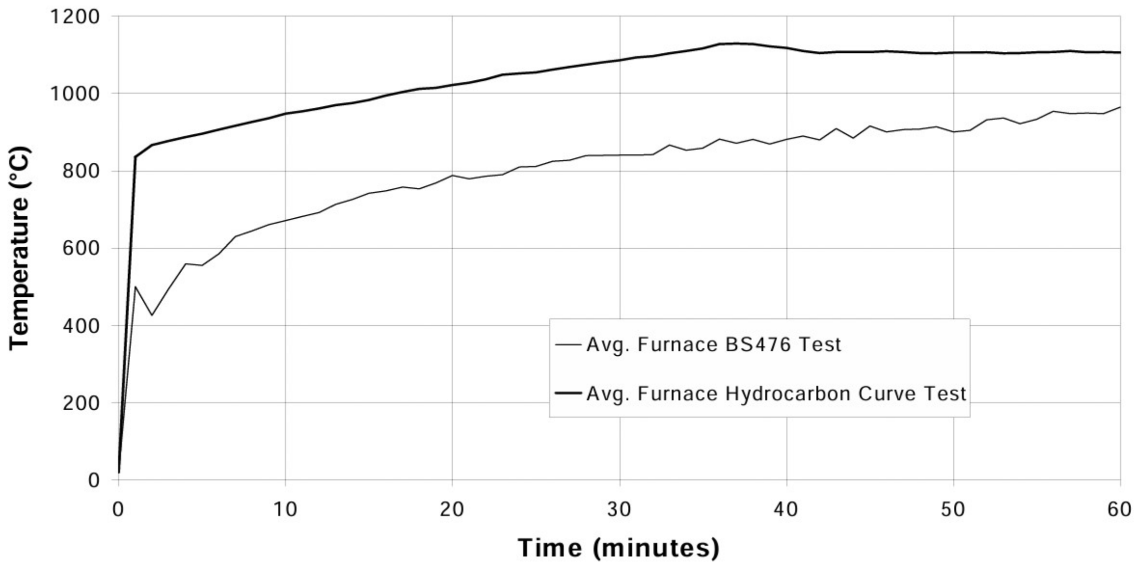

Figure 13. Previous Experimental Result: Fire Curve

Table 5. Compressive Strength from Eurocode 2 of Reinforced Concrete Slabs at Varying Temperature Levels and Fire Exposure Durations

Sample	Temperature Level (℃)	Time Exposure (Min)	Compressive Strength from Eurocode 2 Result (MPa)
1	200	30	39.9
2	400	60	31.5
3	600	90	18.9
4	800	120	6.3
5	1000	150	1.68
6	1200	180	0

Table 6. Regression Statistics Result of Compressive Strength Reduction vs Temperature Level and Compressive Strength Reduction vs Time Exposure

Statistics of Regression	
Multiple R	0.97231435
R^2	0.945395195
Adjusted R^2	0.931743994
Standard Error	4.331152272
Observations	6
F	69.2536271
Significance F	0.001139132

Based on the summary in Table 7, the regression coefficient indicates a significant negative effect of temperature on compressive strength. Thus, the (1) estimated model can be expressed as:

$$y = 46.536 - 0.0431 \ \ \mathrm{TL} \quad (1)$$

Where y is the reduction in compressive strength due to increasing temperature, and TL is the temperature level (℃).

Table 7. Summary of Regression Coefficients for Temperature Level

	Intercept	Temperature level
Coefficients	46.536	-0.0431
Standard Error	4.0321	0.0051
t Stat	11.5414	-8.3219
P-value	0.0003	0.0011
Lower 95%	35.3411	-0.0575
Upper 95%	57.7309	-0.0287
Lower 95.0%	35.3411	-0.0575
Upper 95.0%	57.7309	-0.0287

The 95 percent interval in Table 8 shows that the time exposure coefficient ranges from -0.3830 to -0.1914, which excludes the point (zero). This implies that compressive strength consistently decreases as exposure time increases. The relationship between compressive strength reduction and exposure time can be expressed as (2):

$$y = 46.536 - 0.2872 \ \ \mathrm{TE} \quad (2)$$

Where y is the compressive strength reduction due to increasing temperature, and TE is the time exposure (Min).

Table 8. Summary of Regression Coefficients for Time Exposure

	Intercept	Time Exposure
Coefficients	46.536	-0.2872
Standard Error	4.0321	0.0345
t Stat	11.5414	-8.3219
P-value	0.0003	0.0011
Lower 95%	35.3411	-0.3830
Upper 95%	57.7309	-0.1914
Lower 95.0%	35.3411	-0.3830
Upper 95.0%	57.7309	-0.1914

Figure 14 displays the correlation between the reduction of compressive strength and temperature level at high temperatures. As seen, compressive strength is greatly reduced at high temperatures. The decrease at 200 ℃ is approximately 5%, and that means that the cement paste is early deteriorating and moisture is being lost. At temperatures above 400 ℃, it decreases to approximately 25%, and this is possibly due to the loss of moisture in calcium hydroxide and the dissimilar thermal expansion of aggregates and cement paste. A more intense drop is noticed at temperatures above 600 ℃ when the strength decrease is about 55 percent, indicating severe cases of microcracking and structural degradation. Above 800 ℃, the remaining strength decreases significantly to less than 15 percent and nearly zero at 1000 ℃ to 1200 ℃, indicating almost complete loss of load-bearing capacity. The regression coefficient of temperature indicates a continuous degradation trend, and strength loss increases faster as higher thermal limits are reached. This behavior is consistent with post-fire observations in which concrete demonstrates surface spalling, increased porosity, and a brittle mode of failure. As a result, the reinforced concrete members subjected to temperatures above 600 ℃ can no longer meet serviceability and ultimate limit state requirements, even after cooling.

In Figure 15, the strength of compression of the RC slab decreases significantly with increased time in fire. The initial thermal cracking and dehydration cause a 5% loss of strength at approximately 30 minutes. It reduces further to about 25 percent and 55 percent at 60 and 90 minutes, respectively, as the heat further destroys the concrete matrix. At 120 minutes, the compressive strength is reduced by approximately 15 percent, and at 180 minutes, the compressive capacity is almost lost.

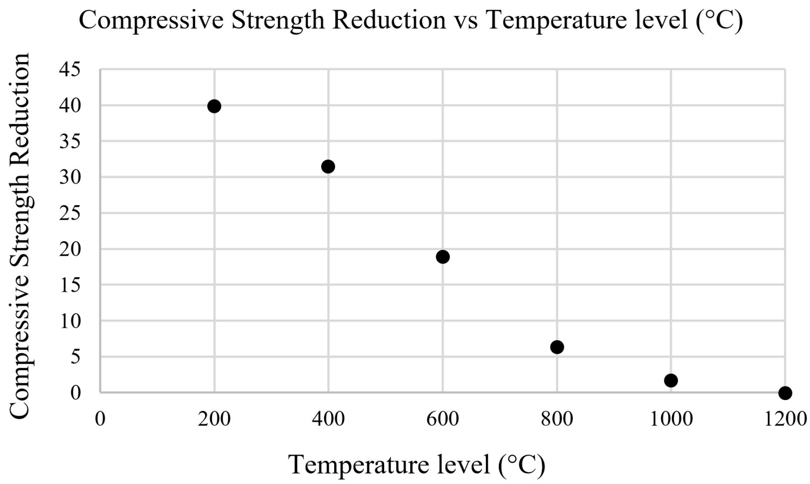

Figure 14. Compressive Strength Reduction vs Temperature level (℃)

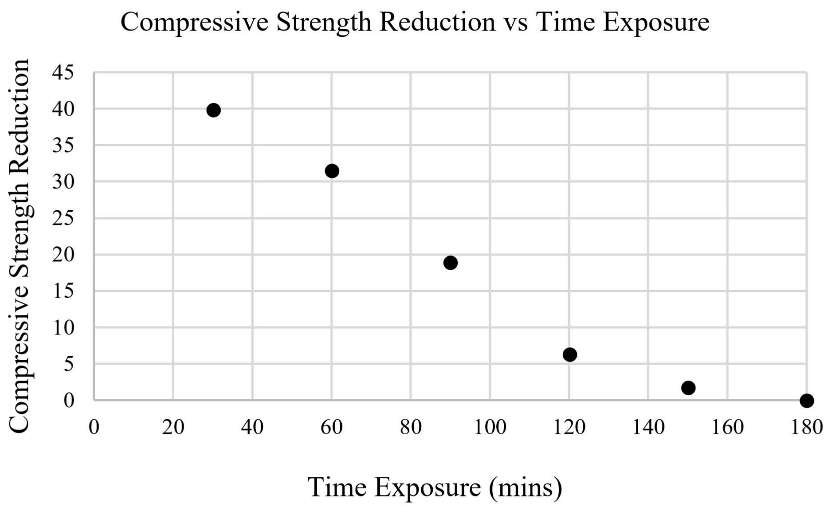

Figure 15. Compressive Strength Reduction vs Time Exposure

3.6. Comparison of Analysis of Prediction Modeling

Equations indicate that compressive strength also decreases with time and temperature exposure at varying rates. Based on the independent variable in Equation (1), the temperature reduction rate is 0.0431, which is lower than that for the independent variable of 0.2872 time exposure. This implies that as temperature increases, it causes a loss in strength, and exposure time affects the strength of compression of the slab much more. A steeper slope in the time exposure equation implies that long-term heating causes cumulative damage, including cracking, loss of moisture, and chemical decomposition of cementitious compounds. In contrast, temperature alone with an insufficient exposure time causes comparatively less strength reduction. Thus, the findings indicate that time exposure plays a more significant role in compressive strength decrease under fire conditions, and the necessity to consider both the intensity of thermal effects and the duration when examining the resistance of fire for RC slabs.

4. Conclusions

The proposed Finite element modeling Approach in Evaluating Fire-Induced Damage in Reinforced Concrete Slabs has been developed and presented in this paper. Through coupled thermal–structural analysis, the model successfully simulated heat transfer, deformation, strain distribution, and crack development consistent with experimental data and Eurocode 2 provisions. The proposed methodology creates a finite element model and compares it to the previous experimental model. The close correlation between simulated and experimental deflections confirmed the reliability of the FEM framework, with a difference of only 1.484 mm. Regression analysis showed that temperature and exposure time have a significant impact on the compression strength of RC slabs, and the effect of exposure time is stronger. The results confirm that ANSYS finite element analysis is a useful and cost-effective tool to evaluate the performance of fire and structural integrity of post-fire RC slabs. The approach enhances understanding of thermal-mechanical interactions and performance-based fire design and retrofitting, aiding the creation of safer and more resilient infrastructure, in accordance with Sustainable Development Goals 9 and 11. Future studies are recommended to include other parameters like moisture migration, pore pressure, spalling, support conditions, mesh convergence analysis, and temperature-dependent bond slip behavior between steel reinforcement and concrete under more realistic fire conditions. Combining machine learning and FEM also has the potential to enhance predictive performance and speed of fire performance evaluation of reinforced concrete structures. Additionally, the FEM approach can be used by structural engineers to calculate the residual strength of fire-induced damage to RC slabs without immediate destructive testing. Identify the critical region that is prone to damage, such as deflection, cracking, and compressive strength degradation. Analyzing whether fire-damaged slabs should be repaired, strengthened, or replaced.

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